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Experimental validation of a distributed algorithm for dynamic spectrum access in local area networks

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***Abstract*—Next generation wireless networks aim at a significant improvement of the spectral efficiency in order to meet the dramatic increase in data service demand. In local area scenarios user-deployed base stations are expected to take place, thus making the centralized planning of frequency resources among the cells, a non-viable solution. Cognitive Radio (CR) and Dynamic Spectrum Access (DSA) are the research paradigms which are expected to provide the network nodes the capabilities for an autonomous and efficient selection of the spectrum resources. In this paper we present the first experimental activities with the Autonomous Component Carrier Selection (ACCS) algorithm, a distributed solution for interference management among small neighboring cells. A preliminary evaluation of the algorithm performance is provided considering its live execution on a software defined radio network testbed. The obtained experimental results confirm the performance trends obtained from prior simulation studies. The analysis in dynamic environment conditions also allowed identifying the utilization of static thresholds in the decision making process, as a critical aspect for the optimization of network capacity.**

I. INTRODUCTION

Future generation mobile wireless networks are expected to cope with the dramatic increase of data services demand. In particular, very high data rate in local-area (LA) is a challenging requirement when considering the scarcity of available spectrum resources in licensed bands. The network setup in indoor home/office environments is expected to be characterized by dense and uncoordinated deployment of access points (APs), thus making the inter-cell interference the major limiting factor for boosting the network performance. Dynamic Spectrum Access (DSA) and the broader concept of Cognitive Radio (CR) [1] are research paradigms which are expected to provide the required spectrum flexibility to cope with the unplanned usage of frequency resources.

The development of CR/DSA concepts has been characterized by extensive theoretical work; network distributed algorithms in particular, have been typically validated by using Monte Carlo system level simulations. Despite the extensive simulation results, both the academia and the industry have shown a growing interest for experimental studies providing more tangible evidence of the algorithms effectiveness. In this sense, the implementation of large network testbeds enables the investigation of environmental properties which are difficult to comprehensively model in simulators. Examples of such aspects are the impact of dynamic environment and terminals mobility. An experimental testbed enables also the investigation of real-time execution issues as well as practical system limitations introduced by the hardware inaccuracies. A considerable amount of work has been presented in literature in relation to the development of platforms and testbeds for CR [2]. The majority of the conducted experimental activities with novel CR concepts, relates to advanced spectrum sensing techniques, physical (PHY) layer design and DSA solutions for opportunistic spectrum access. Nevertheless, algorithms for interference coordination among nodes have, so far, received little attention. A more extensive coverage of recent experimental activities with CR/DSA platforms can be found in [3].

In this paper we select the Autonomous Component Carrier Selection (ACCS) algorithm [4] for the implementation and experimental analysis on a network testbed. ACCS is a DSA algorithm for inter-cell interference management, which is characterized by the distributed execution of the decision making process over the APs aided by an inter-node control channel for cells coordination. The performed experimental activities intend to evaluate the algorithm performance with specific attention to the impact of variable cardinality of the available set of resources, user terminals position and dynamic channel conditions.

The paper is organized as follows. An overview of the ACCS algorithm is given in Section II. A description of the testbed architecture and the implemented system solutions are presented in Section III. Section IV describes in detail the experimental activities and the obtained results from the algorithm execution. Future developments of the experimental work and conclusions are reported in Section V.

II. AUTONOMOUS COMPONENT CARRIER SELECTION ALGORITHM

ACCS is a DSA algorithm which targets the problem of spectrum resource management among femtocells in indoor scenarios. The interest in ACCS relates to its lightweight distributed decision making process which enables a flexible reuse of the frequency resources in the network, thus minimizing the mutual interference and improving channel capacity [4]. ACCS assumes the available spectrum to be divided in a number of Component Carriers (CCs) which are shared among the APs, named evolved NodeBs (eNBs), according to the 3rd Generation Partnership Project (3GPP) terminology. The DSA decision making process occurs locally on the eNBs, but relies on shared information about usage of CCs and inter-cell interference coupling. These features allow the algorithm to be executed on devices with limited channel sensing capabilities, at the expenses of a common control channel in the network. The required sensing information used by ACCS is limited to the Reference Signal Received Power (RSRP) measurements in respect to neighboring eNBs. The ACCS decision process and the control data exchange are executed periodically on a time-frame basis. The ACCS framing is supposed to be rather slow compared to baseline Radio Resource Management (RRM) techniques (e.g., time/frequency domain packet scheduling). Further information about ACCS can be found in [5] and [6]. In the following subsections, brief descriptions of the main ACCS procedures implemented in the testbed are provided.

A. Component Carriers selection procedures

In ACCS the available CCs are divided between a Base CC (BCC), which is intended to be the main communication carrier between the eNB and the UEs, and a set of Supplementary CCs (SCCs) providing additional channel capacity. ACCS aims at ensuring the highest reliability of the BCC (a single BCC is always allocated in the cell) especially in conditions of high interference. ACCS also dynamically enables the allocation of the SCCs in order to meet the cells data traffic demands. In relation to the BCC and SCCs selection procedures, the underlying principle of ACCS consists in enabling the reuse of frequencies in the network under the condition that no intolerable interference is generated by an eNB towards a neighboring cell. The conservative approach in spectrum allocation, enforced by ACCS, aims at the minimization of the network outage probability.

B. The Background Interference Matrix

In order to acquire general knowledge about interference coupling with the neighbors, eNBs can exchange spectrum allocation information and a background interference matrix (BIM) over the control channel. The BIM is a data structure which contains information about inter-cell interference coupling, in the form of estimations of Carrier to Interference (C/I) power ratio, i.e. the ratio between the useful and the interference power which would occur in case two nodes share the same CC. C/I estimations are computed from RSRP measurements at the UE side. In ACCS a certain SCC can be allocated by a node only in case the estimated C/I value, with respect to all the cells occupying the same CC, is above a predefined threshold. Different thresholds are defined for BCC and SCCs. The BCC threshold is typically more restrictive. SCCs can be de-allocated in case of decreased traffic demand or unsatisfactory channel quality experienced in the cell.

III. ACCS TESTBED SETUP

A network testbed has been designed in order to enable the runtime execution and support the experimental activities with ACCS. The developed testbed relies on software defined radio (SDR) equipment featuring the Ettus USRP N200 hardware [7] and host computers equipped with the ASGARD software platform [8]. The radio-frequency front-end consists in the Ettus XCVR2450 daughterboards, able to operate in the 2.4 and 5 GHz bands. The equipment setup is shown in Figure 1.

Figure 1 - Testbed node hardware setup: USRP board and host PC

A general overview of the ACCS testbed architecture is given in Figure 2.

The ACCS testbed features two types of nodes:

- **eNB**. The eNB is responsible for the ACCS algorithm execution: the ACCS decision engine dynamically selects the BCC and periodically triggers the reconfiguration of the used SCCs. The generated ACCS control data is sent broadcast over the control channel.
- **UE**. The UE periodically provides the affiliated eNB with sensing information about the useful signal power as well as from the interfering eNBs.

The developed PHY layer for both the eNB and UE enables the RSRP measurements from multiple nodes. Orthogonal frequency pilot sequences across the allocated CCs have been univocally associated to the eNBs. Pilots are generated in the frequency domain and then converted to time domain through Inverse Fast Fourier Transform (IFFT).

Frequency spacing between the pilots and power sensing at the receiver have been designed for being robust to the non-idealities of the USRP boards such as frequency offset and phase noise. All the USRP boards in the testbed have been calibrated with the aim of aligning transmit power and effective receiver gain within 1 dB, thus ensuring consistent RSRP measurements among multiple nodes. In our current testbed, the PHY layer is only used for signal power measurement purposes, while the whole data exchange (e.g., spectrum allocation information and BIM) occurs over a parallel backhaul network (based on Ethernet or WiFi).

The backhaul infrastructure, depicted in Figure 2, is used also for experiment control and testbed data collection. The ACCS control channel is emulated by a centralized unit that routes the control data among the nodes. The feedback channel connecting the UEs to the affiliated eNBs is also emulated and enables the reporting of the downlink (DL) RSRP measurements.

IV. ACCS EXPERIMENTS

Prior simulation studies [6] allowed characterizing the performance of a network running the ACCS algorithm. In particular, improved outage channel capacity in respect to Reuse 1 (i.e. each node is transmitting over the whole bandwidth corresponding to the number of configured CCs) is achieved in case of heavy data traffic conditions.

In this work, a set of experimental trials have been conducted in order verify these findings in a realistic deployment scenario. Moreover, experiments have been also performed in

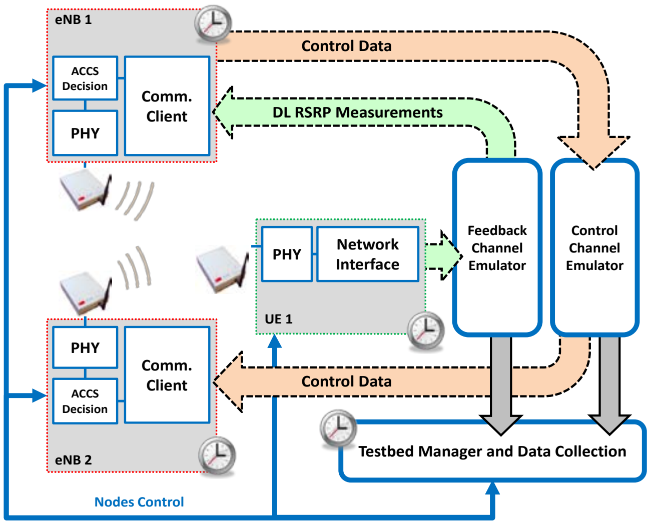

Figure 2 - ACCS Testbed architecture. Connections between network nodes and the testbed backhaul infrastructure are visible. All units in the testbed can be time synchronized for the automatic execution of experimental runs.

order to evaluate the impact of UE terminal positioning and channel dynamics. According to the indoor deployment assumption of ACCS, the testbed nodes have been placed inside the office premises of Aalborg University. The environment is characterized by several office rooms on the same building floor, arranged in a double stripe fashion with a corridor in between (see Figure 2). An identical spatial deployment of the nodes is considered for all the experiment trials: the setup features 6 testbed nodes deployed across 3 cells obtained by considering 1 eNB and 1 UE per cell. The cells are confined in 3 separate rooms. Two specific configurations for cell 3 have been foreseen: in position a) the eNB 2 is placed very close to the UE 3, thus generating strong interference. Position b) instead, reduces this effect. Despite the limited number of nodes, such deployments provide challenging and diversified interference coupling combinations for the ACCS performance evaluation.

All experiment trials share common system configuration parameters which are here briefly described. The I/FFT size is set to 1024, offering sufficient granularity for the spectrum division up to 4 CCs and the frequency allocation of the reference pilots across the same CC. A minimum spacing of 180 kHz between adjacent pilots is set in order to avoid power leakage due to the USRPs frequency offset.

The algorithm execution iteration period (ACCS frame) is of 400 ms while the UE measurements reporting period is of 200 ms. The considered traffic model is full-buffer: once the UE connects to the cell, the eNB attempts to allocate the maximum number of SCCs allowed according to the channel configuration.

The ACCS algorithm is executed on the testbed in real-time, thus generating time data traces of the eNBs control data and UEs RSRP measurements. These experimental results allow generating network-wide statistics about downlink SINR experienced in the cells, and computing the corresponding estimated capacity which is obtained through Shannon mapping [9]. It is to be noted that the Signal to Interference

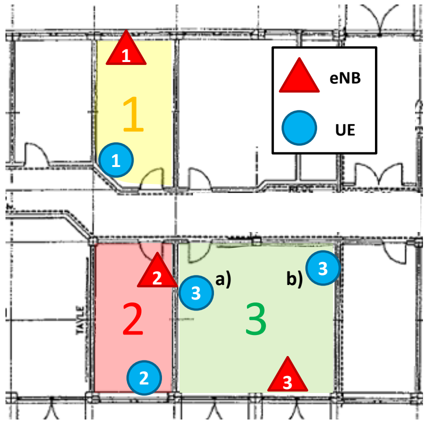

Figure 3 - Experiments Deployment Scenario. UE in cell 3 is moved from position *a* (Experiment 1) to position *b* (Experiment 2)

and Noise Ratio (SINR) is first measured on the narrowband pilots, and then scaled to the effective emulated bandwidth of the used CC configuration. The total system radio bandwidth is of 12.5 MHz, while the effective bandwidth occupied by the transmitted pilots and also the emulated bandwidth for capacity estimation, is of 10 MHz. Transmission power per CC is 0dBm.

A. *Static environment algorithm analysis*

The goal of the first experiment (Experiment 1) is to verify the behavior of the network in a static environment scenario. The impact of a different number of CCs on the network performance is investigated in particular. In order to meet the static environment assumption, the experiments runs have been executed during night hours. The experiment deployment considers the UE 3 placed in position *a* according to Figure 3. Iterations with 2, 3 and 4 CCs have been performed. ACCS performance is then compared with standard Reuse 1. A single run of the experiment consists in the steps reported below:

- eNBs are activated sequentially and a single BCC is selected per cell.
- UEs are activated sequentially within an interval of few ACCS frames: the maximum number of SCCs allowed by the algorithm is allocated in the cell as soon as the UE connects, and before the following UE is activated.

Nodes activation sequences have a considerable impact on the final CC allocation for the different cells especially among highly-coupled cells. The full buffer traffic model favors indeed a wider allocation of resources for the first cell activated in time. Allocated SCCs are not released unless the channel quality becomes unsatisfactory. In order to cover all the possible combinations of eNB and UE activation sequences over 3 cells, 36 experiment runs were designed. Multipath fading variability is introduced by repeating the experiment over 10 different carrier frequencies ranging from 4.91 to 5.81 GHz. The amount of experiment runs for each CC configuration is therefore 360, for total of 1080 runs considering the aforementioned 3 configuration cases.

The obtained results in terms of downlink Shannon channel capacity are presented in Figure 4. Every point in the

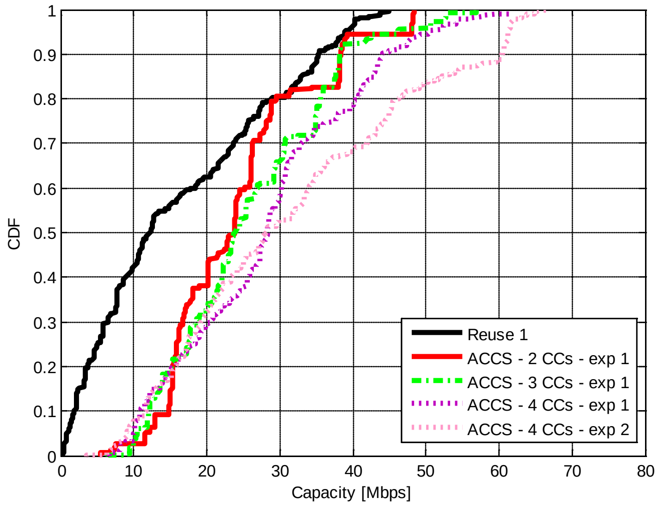

Figure 4 – CDFs of the downlink Shannon Capacity in the cells

cumulative distribution functions (CDFs) corresponds to the capacity estimated for a specific cell (eNB-UE link) at the end of the experimental run, after all nodes have been activated and SCCs selection has occurred. The curves show a general gain of ACCS in comparison with Reuse 1. As expected, ACCS performs better in the lower percentile of the CDF, meaning in the case of highly interference-coupled cells. Lower gain is instead achieved in the best cases. The obtained results also show that moving from Reuse 1 to the 2 CCs configuration is sufficient to orthogonalize the allocation of frequency resources in most of the high interference cases, thus obtaining the major gain contribution. Such behavior is also coherent with the network topology where 2 cells (2 and 3) are strongly interference-coupled while one (cell 1) is more isolated. Increasing the CCs cardinality provides a decreasing gain margin, enabling however, further chances of fractional frequency reuse and thus improving capacity.

B. *UE position impact*

The deployment scenario and the achieved network performance in Experiment 1 are characterized by the high interference from eNB 2 to UE 3. Different interference conditions may impact the ACCS allocation of resources thus providing significant variations in the available capacity in the cells. A second experiment (Experiment 2) has been then conducted in order to investigate such aspect. In respect to Experiment 1, the UE 3 has been moved to the other side of the room 3 (position *b* in Figure 2) in order to maximize the pathloss with respect to eNB 2. The execution of Experiment 2 follows the same procedure as experiment 1. A single channel configuration with 4 CCs is considered.

Statistics about CCs utilization obtained from the experiments have been summarized in Table I and Table II. The values reported are averaged over the entire experimental session considering 360 runs. Data in the tables show that the variation in the level of interference experienced in cell 3 from Experiment 1 to Experiment 2 has a widespread impact on the amount of resources allocated in the entire network. In the first case, cell 2 and cell 3, being extremely interference-coupled,

TABLE I. EXPERIMENT 1 SPECTRUM USAGE OVERVIEW

Cell	**Spectrum usage** (4CCs=100%)	**Shared spectrum resources** (4CCs=100%)		
		Cell 1	Cell 2	Cell 3
1	84%	-	32%	20%
2	48%	32%	-	0%
3	48%	20%	0%	-

TABLE II. EXPERIMENT 2 SPECTRUM USAGE OVERVIEW

Cell	**Spectrum usage** (4CCs=100%)	**Shared spectrum resources** (4CCs=100%)		
		Cell 1	Cell 2	Cell 3
1	95%	-	45%	53%
2	49%	45%	-	5%
3	54%	53%	5%	-

trigger a perfectly orthogonal allocation of their resources by ACCS. In experiment 2 instead, the more isolated position of the UE diminishes the cell coupling thus enabling a better utilization of the spectrum by all the cells. Opportunities for frequency reuse among the cells are also increased, especially looking at cell 1 which is the most isolated in the considered scenario. According to the previous analysis, the results in Figure 4 show an increase in cells' capacity mostly affecting the upper percentile. These specific values are related to the performance of cell 1 which greatly benefits from the increased average spectrum allocation. The lower percentile of the CDF is almost non-affected by the UE movement. This situation is due to the unmodified eNBs interference contributions on the heavily interfered UE in cell 2, which indeed is unable to take advantage from the new scenario conditions.

C. *Dynamic environment algorithm analysis*

The effect of rapid variations in the experienced C/I values in the cells, and SINR estimations over the CCs, can impact the effectiveness of the ACCS allocation. A third experiment conducted with the ACCS testbed aimed then at evaluating the impact of a dynamic environment on the algorithm execution. Human presence in the rooms has been then allowed. The relation between the capacity estimation obtained in such dynamic context, in comparison to the previous static-environment studies has also been analyzed.

Experiment 3 features the same testbed setup as in experiment 1. A fixed channel configuration with 4 CCs, and fixed frequency carrier setting at 5.41 GHz have been considered. In order to acquire results in realistic scenario conditions, the experiment has been executed during working hours.

The office rooms are characterized by different degrees of human activity: cells 2 and 3 are on average, more crowded than cell 1. An experimental run of 1 hour duration (3600 sec) is considered for the analysis.

An overview of the experiment results is provided in Table III. The table reports the time average of cell capacity values ($\overline{X}$), together with the reference values obtained by the same experimental scenario (carrier frequency and activation sequences) in static environment conditions (from Experiment 1). Standard deviation (σ) is also included.

The obtained results confirm the average capacity, for cell 1, comparing to the static environment case. The behavior of

TABLE III. EXPERIMENT 3, CHANNEL SHANNON CAPACITY STATISTICS OVER 1 HOUR

Cell	Reference values from Experiment 1 [Mbps]	$\bar{X}$ [Mbps]	σ [Mbps]
1	57,6	56,3	7,3
2	41,1	13,7	8
3	10,4	39,5	10,4
Network Total	109,1	109,5	9,5

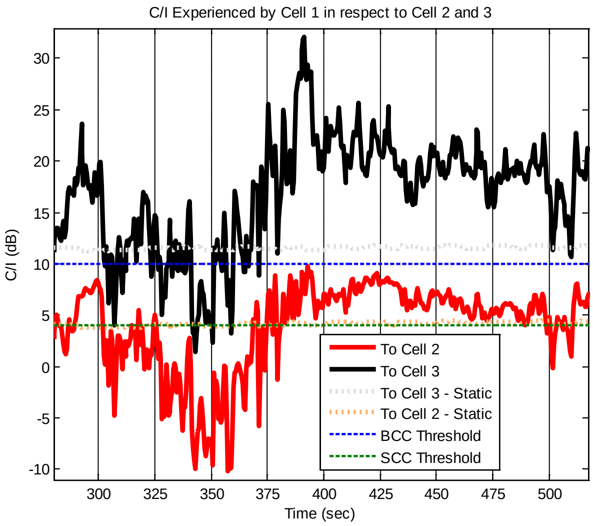

Figure 5 – Exp. 3, snapshot of C/I variations in time measured by Cell 1

cells 2 and 3 is instead different. The analysis of the experiment results indicates that in an extremely competitive traffic scenario, the signal quality variability introduced by the dynamic environment has a negative impact on the most interfered cell (cell 2). Such situation can be explained by the tight relation between the variations of the measured C/I values in the cells, and the performed CCs allocation by ACCS. In order to have a visual understanding of this aspect, a time snapshot of the measured C/I values by cell 1 during an experiment run is provided in Figure 5. The allocation of resources by ACCS is always conditioned by the level of the C/I values in comparison to the pre-defined BCC and SCC thresholds. From Figure 5 it is evident that while in a static environment the measured C/I is almost constant in time, the human activity introduces signal variations which may compromise the equilibrium introduced by the ACCS thresholds.

D. Experimental activities discussion

The performed experimental activities with the ACCS testbed, served as a preliminary validation of the ACCS performance in a realistic operational environment, considering challenging user traffic load in the cells. The obtained results in terms of theoretical channel capacity, confirmed the tendency in performance gains from ACCS in respect to frequency Reuse 1 scheme. The experiments enabled also a better understanding of the impact of UE positioning on the network performance: the movement of a terminal within a single cell may indeed trigger a re-balance of available resources to all neighboring cells. The algorithm proved, however, to cope with all the different scenarios, ensuring a capacity gain of ~500% at the 10% outage users in respect to Reuse 1.

Experiments in a dynamic environment allowed individuating critical areas for the algorithm improvement. In particular the ACCS sensitivity to the high variability of C/I values in respect to fixed thresholds may lead to sub-optimal resource allocations. In respect to this it may be beneficial to investigate the implementation of time-varying thresholds, also considering learning capabilities of the system about the different operational conditions and channel dynamics.

V. CONCLUSIONS

In this paper the first experimental activities and investigations with ACCS, a distributed, carrier based inter-cell interference mitigation algorithm, have been performed in a realistic indoor local-area scenario deployment. A multi-cell network testbed has been developed for this purpose. The experimentation with ACCS focused on the network performance evaluation in both static and dynamic radio environments. Experimental results proved to be compliant to the prior simulation-based findings. The ACCS testbed capabilities are currently being improved in order to investigate fractional traffic load, multiple antenna transmission schemes and combined methods for interference mitigation/cancellation.

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